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14. ABSTRACT

This report results from a contract tasking University of Cambridge as follows: The contractor will investigate yttrium-barium-copper oxide (YBCO) coatings divided into filaments with various widths and separations. AC loss measurements as well as magnetization measurements will be conducted. Experimental results will then be compared with the theoretical models and predictions. Finally, the experimental and theoretical results will be compared with the Slovakian research group results (SPC 014027).

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Report on EOARD Contract No F61775-01-WE028
1May 2001-31 Oct 2001.
AC Loss Minimisation in High Temperature Superconductors

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1. Introduction.

This contract is concerned with the measurement and minimisation of AC losses in superconductors for applications in high speed motors and generators in aircraft. The advent of new coated conductors made of fully aligned YBCO makes this application a practical possibility, due to large reductions in the size and weight of superconducting machines as compared with conventional ones. Although so far only short lengths of material are available it is important to characterise the material and be ready with a design as soon as long lengths can be made. The main obstacle to the use of superconductors in electrical machines in the past has been the AC losses. At helium temperatures, and probably also up to 30K, these have proved unacceptably large. Although it is much easier to remove the heat in liquid nitrogen BSCCO tapes have too low an irreversibility line to be used in the magnetic fields encountered in an electrical machine. YBCO does not suffer from this problem and tapes already produced will carry high currents in high magnetic fields.

The DC properties are very attractive, but to reduce the AC losses it is necessary to use a narrow conductor since the loss per unit volume is proportional to the conductor width. Dr. C. Oberly of Wright Patterson Airforce Base proposed that the coated conductors should be subdivided into narrow strips thereby reducing the losses to an acceptable level, and our experiments are designed to test this proposal.

There are two ways of measuring losses, thermal and electrical. The thermal technique is more straightforward but gives less information and requires fairly large amounts of material. We are therefore using an electrical technique. This has required the construction of new apparatus since the regime of interest has not been explored before. This is because the combination of high magnetic fields and high frequencies (up to 400Hz) needs high powered supplies and generates high voltages. At the same time as developing the experimental techniques, we have also built up expertise in finite element modelling of the current distribution and losses, and explored the possibility of reducing losses by magnetic shielding and special arrangements of conductors.

2. Apparatus.

Our research activity in this period has concentrated on building up apparatus for measuring AC losses in superconducting tapes. Because of the non-ideal geometry of such tapes (their high aspect ratio) and low AC loss signals buried in several orders of magnitude higher unwanted induced voltages, loss measurement is not straightforward and special care has to be taken to measure the losses correctly. We chose a method based on measurement of the loss signal with a lock-in nanovoltmeter. The principle of the method consists of measuring the voltage generated either by a pick-up coil around the sample (when the sample is exposed to an AC magnetic field), or by potential taps soldered directly onto the sample surface (when the sample is fed by a transport current). When the unwanted inductive voltages (which are typically 3 or 4 orders of magnitude higher than the loss voltages) are properly compensated, the lock-in nanovoltmeter measures the loss component voltage, which is the component in phase with the external magnetic field or applied current. If the external magnetic field or applied current is purely

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sinusoidal without any higher harmonics it is sufficient to measure only the fundamental component of the loss voltage with the lock-in nanovoltmeter.

The main problems in building such an apparatus are the following :-
1) to supply a strong high frequency magnetic field.
2) to design a pick-up coil which will give the correct loss signal when the sample tape is oriented at an angle to the magnetic field.
3) to design a suitable compensation coil with a variable signal level which does not contain any loss signal.

We have made a Helmholtz split coil copper magnet for magnetic field generation, see fig.1.

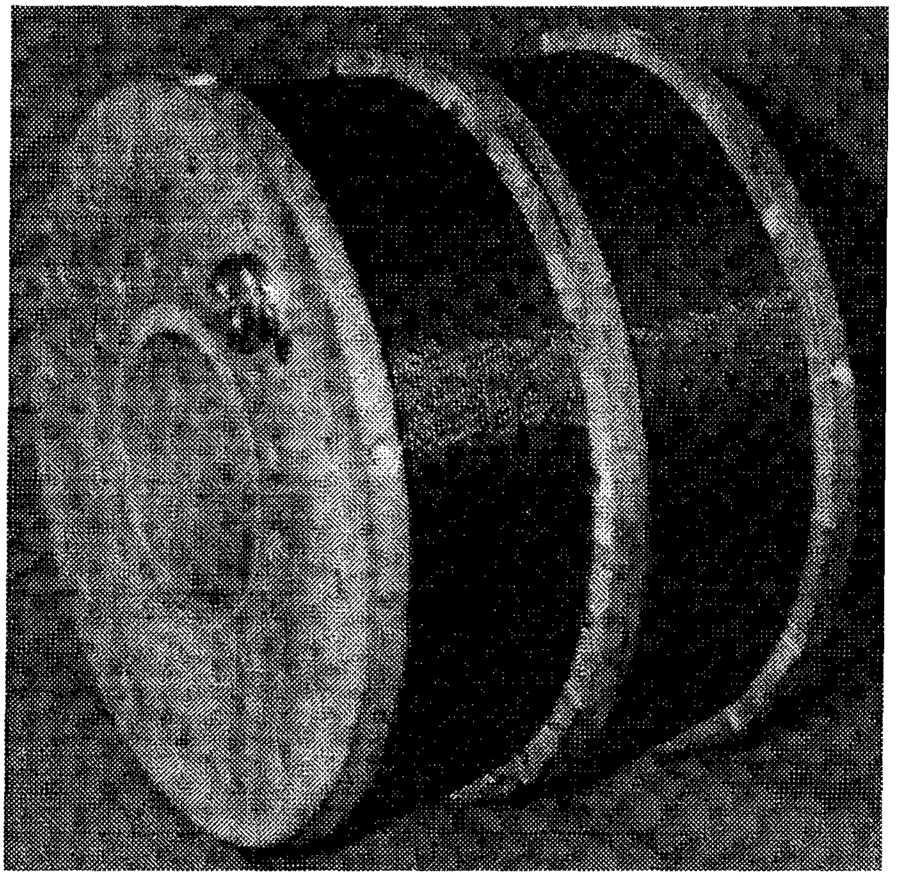

Fig. 1: Cu split coil.

As a conductor a copper cable was used. It consists of seven strands insulated copper wires, each of 0.6 mm in diameter. The twist pitch of the cable is 30 mm. The purpose of using a cable instead of a single thick wire is to suppress the eddy currents in the winding which influence the magnetic field of the magnet, especially at higher frequencies. For the same reason also the former of the magnet was non metallic and made of a fibreglass epoxy. The magnet bore diameter is 91 mm. and the weight 30kg. The resistance in liquid nitrogen is 1.65 Ω and the inductance 0.722 H. The magnetic field constant in the centre of the magnet bore is 0.0147 tesla/amp. The inhomogeneity of the magnetic field is better than 1 % within a cylindrical

volume of diameter 50 mm and length 36 mm. A slot in the magnet (see fig. 1) allows a sample tape with dimensions of up to 10 mm x 50 mm to be inserted into the magnet at different orientations with respect to the magnetic field, and with a transport current always perpendicular to the magnetic field.

The overall cross-section of the cable is 1.98 mm^2 which allows a transport current up to about 28 A(peak) at liquid nitrogen temperature. This corresponds to a peak field amplitude of 0.42 T. However due to the rather high inductance of the magnet even at 60Hz we would have a voltage on the magnet terminals of 5.44 kV_{rms}. Because there are no power supplies available which could give such a power, we have made a bank of capacitors with a variable capacity, which is connected in series with the magnet. The values of the capacities were chosen so that at several typical frequencies the series LC circuit is in resonance, in which case the high inductive voltages on the magnet and on the battery of capacitors are exactly in opposite phase and cancel. The net voltage of such a circuit is purely resistive and we can use a more available power supply. However, the high voltages (in the kV range) are still present on both the magnet and the battery of capacitors during operation, so special care has to be taken when designing such a bank of capacitors, as well as its connections to the magnet, to comply with safety rules. The capacitors must be equipped with bleed resistors, they must be screened and the screening must be earthed and all connections must be insulated.

We were fortunate in being able to buy a power supply from other sources, as this is the most expensive part of the apparatus. It consists of four Kepco units, each can supply 20amps and 20 volts (peak) from DC to 10kHz. They can be connected in any configuration and driven with any waveform so that we can investigate the effect of harmonics if required. With this supply the peak field is 0.3T. The limitation on frequency is set by the dielectric strength of the capacitors and magnet insulation. The voltage should not exceed 4.5kV.

3. Finite Element Modelling.

Using numerical modelling with the Finite Element Method (FEM) the AC loss measurement technique for the tapes in an external magnetic field at different angles was analysed. Contours in the space round the sample were calculated such that the Poynting Vector gave the correct loss. A pick-up coil was designed in the optimal position to maximise the loss signal, and compensating coils were placed where the loss signal is negligibly small. Further developments of the finite element model were used to calculate the effect of magnetic screening of the filaments and to analyse the thermal stability of the conductor.

4. Results and Publications

As pointed out above the main activity in the six months of this contract has been to construct and test the apparatus to measure the loss in the high field, high frequency regime. However the start of the project coincided with the discovery of superconductivity in Magnesium Diboride and we devoted some time to assessing the possibility of this material as a conductor for motors and generators. The results are in references [1-3]. It was shown that this material is much easier to make into wires than either YBCO or BSCCO and that it does not suffer from the problem of weak links. However unless the critical temperature can be raised machines using it will have to operate between 20 and 30K and losses will be a major problem.

In these papers we explored the possibilities of using iron screening to reduce losses. It was found by numerical modelling (using FEM) that 4 concentric iron layers, 50 μm thick each with 50 μm separation, are able to screen out an external magnetic field of 0.4 - 0.5 T, which was higher than expected and comparable to fields in machines. The total losses of such a screened superconducting cylinder (i. e. the losses in the superconductor plus the losses in the iron screens) are more than 3 times lower than in an unscreened superconductor (Fig. 5 in [3]). Also we found an anomalous decrease of the AC susceptibility around 50 K in our Ag-MgB_2 and Cu-MgB_2

wires indicating a possibility of finding superconductivity at elevated temperatures in this compound. In paper [4] a numerical approach to solve the problems of heating, current sharing and stability was developed and applied to Bi-2223/Ag multifilamentary tapes with oxide barriers around the filaments. A similar approach can be applied also to YBCO coated conductors. Paper [5] deals with pulsed laser deposition of epitaxial YBCO/oxide multilayers onto textured metallic substrates. The two kinds of substrates used were NiFe and the recently developed NiCrW. The main problem proved to be substrate oxidation during YBCO growth. The solution was found to be the use of a CeO_2/Pd composite target.

5. Future Work

Future research will be concentrated on AC loss measurements of YBCO coated conductors and on the influence of the substrates on the total losses of the composite tapes as well as on the effect of dividing the tapes into filaments. These measurements will be done at high magnetic fields and at frequencies up to 400Hz.

6. Publications

1) B. A. Glowacki, M. Majoros, MgB_2 Superconducting Conductors for DC and AC Applications. *Studies of Superconductors (Advances in Research and Applications) MgB_2* (ed. A. Narlikar), Nova Science Publishers, Inc., Huntington, New York, Vol. 38 (2001) p. 361 - 396.
2) B. A. Glowacki, M. Majoros, M. E. Vickers, B. Zeimetz, Superconducting Properties of Powder-in-tube Cu-Mg-B and Ag-Mg-B wires. *Presented at EUCAS'01, Copenhagen, 26 - 30 August 2001. (cond-mat/0109085)*
3) B. A. Glowacki, M. Majoros, MgB_2 Conductors for DC and AC applications. *Invited paper, presented at EUCAS'01, Copenhagen, 26 - 30 August 2001. (cond-mat/0109114)*
4) M. Majoros, B. A. Glowacki, A. M. Campbell, Stability of Bi-2223/Ag Multifilamentary Tapes with Oxide Barriers - A Numerical Simulation. *Presented at EUCAS'01, Copenhagen, 26 - 30 August 2001.*
5) R. I. Tomov, A. Kursumovic, D. A. Kang, B. A. Glowacki, M. Majoros, J. E. Evetts, A. Tuissi, E. Villa, Pulsed Laser Deposition of Epitaxial YBCO/oxide Multilayers onto Textured Metallic Substrates for Coated Conductor Applications. *Presented at EUCAS'01, Copenhagen, 26 - 30 August 2001.*

Report on EOARD Contract No F61775-01-WE92
31Oct 2001-31 Jan 2002.
Extension to AC Loss Minimisation in High Temperature Superconductors

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1. Introduction

In this period of research we concentrated our efforts on AC loss measurements of YBCO coated conductors on textured metallic substrates made in Cambridge. Several samples were prepared by pulsed laser deposition on two different substrates: NiFe and the recently developed NiCrW. The samples differed in sintering conditions and in buffer structures. The two best samples - with the highest critical temperature - on two different substrates were chosen for the AC loss study. The onset critical temperature of both the samples was 85 K, however zero resistance was at about 20 K, i.e. the transitions were very broad. For this reason we decided to perform loss measurements at 5 K using a SQUID magnetometer, since the high frequency equipment will not go down to this temperature.

2. Results

The sample architecture was $YBCO/Y_2O_3/CeO_2$:Pd/NiFe and $YBCO/Y_2O_3/YSZ/CeO_2$:Pd/NiCrW. Both samples had a thickness of YBCO of 350 - 370 nm and the buffer structure thickness was 200 nm. The thickness of NiFe and NiCrW substrates was 35 μm and 90 μm, respectively.

The measurements were performed in applied magnetic fields up to ±6 T perpendicular to the broader face of the tapes. The critical current densities determined from magnetisation at 3 T for the sample on NiFe and NiCrW substrates were 6.24×10^8 A/m^2 and 1.06×10^9 A/m^2, respectively. Their magnetic field dependence follows the Kim relation $J_c=a/(b+|B|)$. To be able to subtract the loss contribution from the substrates the substrates alone with buffer layers - CeO_2:Pd/NiFe and CeO_2:Pd/NiCrW - which underwent the same heat treatment as the original samples were also measured. Hysteresis losses for 1 cm wide tapes (in Joules per cycle per metre length) are higher in the sample with NiCrW substrate than in that with NiFe in the whole magnetic field region ($\mu_o H_{ext}$=0.01 T - 6 T) roughly by a factor of 2, reflecting the sample $J_c(B)$ dependencies. Also the magnetic field dependence of the losses roughly follows a $(\mu_o H_{ext})^n$ dependence with $n \leq 1$. These facts indicate that both samples are in fully penetrated states, even at the lowest applied magnetic fields ($\mu_o H_{ext}$=0.01 T). (In a partially penetrated state the losses would follow $(\mu_o H_{ext})^n$ with n=4 if the $J_c(B)$ dependence follows the Kim relation, and would be approximately inversely proportional to J_c).

An YBCO layer of the sample on the NiCrW substrate was then cut to form 2 filaments and measured again in a perpendicular magnetic field as well as in a field at an angle of 45^o with respect to the tape face. In a perpendicular magnetic field the hysteresis losses of 2 filaments were a factor of about 0.6 lower than the losses of the original single filament, so subdivision is indeed a practical technique for reducing losses. The losses at 45^o roughly scaled as cos(45^o) indicating that the component of the magnetic field perpendicular to the tape face dominates the losses as expected from theory.

The influence on the magnetisation of dividing a monocore tape into 2 and 4 filaments was numerically modelled using the critical state model with a constant critical current density. For full penetration and a perpendicular magnetic field the magnetisation decreases proportionally with increasing number of filaments. However, due to the high aspect ratio of the tape, there is no visible effect in a parallel magnetic field. Hysteresis losses in metallic

substrates - CeO_2:Pd/NiFe and CeO_2:Pd/NiCrW - were substantially lower than the total losses of the composite tapes. The losses in NiFe substrate at $\mu_o H_{ext}$=3 T (perpendicular to the tape face) were more than 1 order of magnitude lower than the total losses of the composite tape and those in NiCrW were lower by more than 4 orders of magnitude. Magnetisation characteristics of the substrates were measured also at T= 77.3 K and T=100 K. It was found that the magnetisation of the NiFe substrate does not depend on temperature in this temperature range. On the other hand the magnetisation of NiCrW substrate decreases with increasing temperature and becomes small at T=77.3 K (about 40 times lower than that of NiFe).
The main conclusions which can be drawn from these experiments are the following. It was shown experimentally that dividing a tape into filaments reduces ac losses in perpendicular magnetic field roughly in proportion to the number of filaments. The losses in both NiFe and NiCrW substrates are substantially lower than those in the composite tape, however the losses in NiCrW are much lower than those in NiFe.

3. Magnet Screening

Besides the possibility of a significant AC loss reduction by a magnetic screening of the external magnetic field up to about 0.5 T mentioned in our previous report, we would like to draw attention also to a similar possibility in self-magnetic field. The principles were established before the contract started and reported in ref.1. However we have recently been investigating the application of the method to the particular range of parameters likely to be met in motors. Using ferromagnetic sheets as shown in Fig. 1 there is a possibility of self-field loss reduction of more than a factor of three.

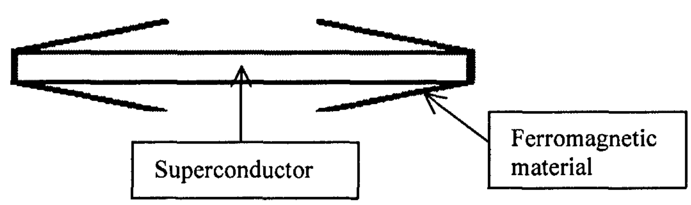

Fig. 1: a) Geometry of the superconducting tape and the ferromagnetic sheets.

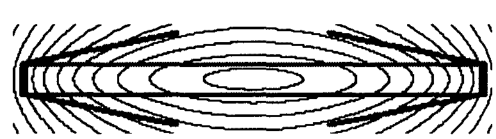

Fig. 1: b) Magnetic field lines (scale 10^{-5} Wb) of a current-carrying conductor (current density $10^9 A/m^2$) when the relative magnetic permeability of the ferromagnetic material μ_r =1.

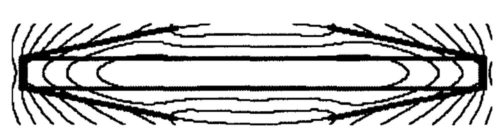

Fig. 1: c) Magnetic field lines (scale 10^{-5} Wb) of a current-carrying conductor (current density $10^9 A/m^2$) when the relative magnetic permeability of the ferromagnetic material μ_r =60. The transport AC loss decreases more than 3 times.

The simulation was made using the Finite Element Method with the following parameters:-

Superconducting tape 3mm wide and 0.2mm thick, the thickness of the ferromagnetic sheets 6μm, their length 1 mm and the angle with the surface of the tape 11.5°. Numerical simulations were made using the critical state model with J_c=const. The scale of the magnetic field lines in Fig. 1b and Fig. 1c is the same so a direct comparison of the figures is possible. The presence of the ferromagnetic sheets decreases the magnetic field in the superconductor and consequently the losses. The AC loss is more than 3 times lower than in a tape without the ferromagnetic sheets.

The publications that occurred in the report period are referenced in the list of publications. Publication [1] reflects our final results on a possibility of achieving a higher critical temperature in MgB_2 material. Publication [2] will summarise the results outlined in the present report.

4. Future Work

Our future research will be concentrated on AC loss measurements on samples of higher quality developed at Wright Patterson Airforce Base. These will be carried out in the fields and at frequencies relevant to motors and generators. We will continue to develop theoretical model for ac loss calculation in coated conductors and analysis of their cryogenic stability.

List of publications:-

1) 1) M. Majoros, B. A. Glowacki, M. E. Vickers, 50K anomalies in superconducting MgB_2 wires in copper and silver tubes. *Supercond. Sci. Technol. 15 (2002) 269.*

2) M. Majoros, R. I. Tomov, B. A. Glowacki, C. E. Oberley, A. M. Campbell, Hysteresis losses in YBCO coated conductors on textured metallic substrates. *Abstract Submitted to Applied Superconductivity Conference, Houston, TX, USA, 4 - 9 August, 2002.*

3) M. Majoros, B. A. Glowacki, Studies of High Temperature Superconductors, Vol. 33, AC Losses and Flux Pinning and Formation of Stripe Phase (ed. A. Narlikar) (2000) p. 1 – 51, (This work predates the contract reported on).